results from loading. The thrust modulus, E, computed from triplets of data for definite steps of pressure (1, 2, 1), (2, 3, 2), etc., kg. (i.e., 15, 25, etc., kgm. per square centimeter), are given in figure 3. They increase in marked degree with the load. Turning the rods down to smaller diameters successively and testing them in turn, no essential difference in the results was apparent. With rods of high rigidity like glass, brass, steel, only about one-half of the probable modulus can be reached with rods of the above dimensions. The remainder is lost in the small dislocations within the apparatus. These rods[3] must not be more than 1 or 2 mm. thick and enclosed in corresponding sheaths, to be available in an apparatus-like figure 1. Tentative[4] as the results are, however, they are interesting, inasmuch as the dependence of the elastics of a rod on its molecular instabilities will most probably be clearer in case of bodies of light structure like the organic bodies. The whole phenomenon is very much like the condensation of a vapor, requiring higher pressures to condense the instabilities and lower pressures for their release or evaporation, as it were. Deformation proceeds at a rapidly retarded rate through infinite time.[5]

[1] These PROCEEDINGS, 3, 1917, (412).

[2] Shown in the side elevation, figure 1*a*, with the offsets removed. The fibres d and d_1 are tightly stretched.

[3] Thus in case of steel rods like the above, per kg of load, $\Delta N/\Delta P = 44 \times 10^{-6}$ cm., which is too small for any micrometer.

[4] I have thus far been unable to arrive at a trustworthy distinction, except in magnitude, between the deformations within the apparatus and those of the rods themselves.

[5] From a report to the Carnegie Institution of Washington, D. C.

SUBLACUSTRINE GLACIAL EROSION IN MONTANA

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The mountains of northwestern Montana and northern Idaho are characterized by two classes of deglaciated forms. The forms of one class are the work of relatively small, local glaciers, and are limited to the loftier ranges in which cirques, excavated in the higher slopes, lead down through well-scoured troughs to terminal moraines on the mountain flanks or on the open ground of intermont basins. The forms of the other class are the work of great Canadian glaciers and are limited to the sides and floor of the larger valleys. Two such glaciers crossed the international boundary, as shown in figure 1, truncated the side spurs

of the valleys that they followed, and locally overdeepened the valley floors into lake basins, at the farther end of which large terminal moraines were deposited. One of the Canadian glaciers moved southward along the large longitudinal valley known as the Rocky Mountain trough and, after reënforcement from Glacier National park, spread out in the broad Flathead basin; a brief account of its erosional work, as well as of the

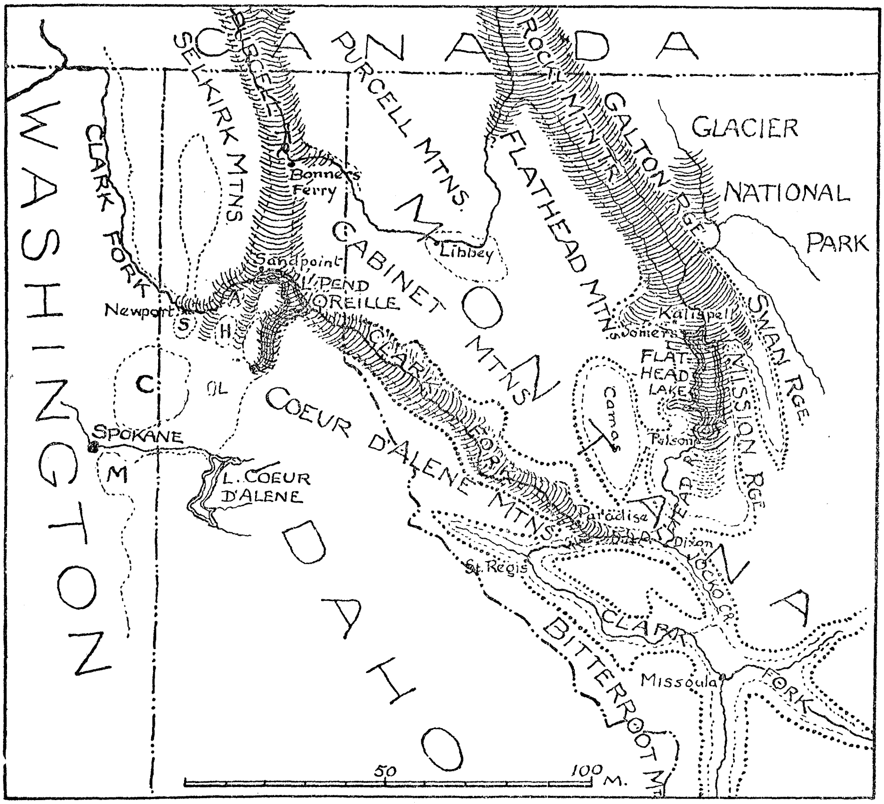

FIG. 1. OUTLINE MAP OF CANADIAN GLACIERS FORMERLY INVADING NORTHWESTERN MONTANA AND NORTHERN IDAHO.

work of local glaciers in the adjoining Mission range, was given in these PROCEEDINGS two years ago,[1] and a somewhat fuller statement has been published in the *Geographical Review*.[2] The other Canadian glacier moved southward along the Purcell trough farther west and invaded the valley of Clark fork of the Columbia river; its work is here summarized. A full report of the Shaler Memorial investigation on which these special studies are based will probably appear in the *Annals of the Association of American Geographers*.

The western glacier may be named after two deep lakes, Kootenay and Pend Oreille, the basins of which it excavated, one to the north, the other to the south of the international boundary. Lake Kootenay is a superb sheet of water of simple outline, ocupying an elongated and greatly overdeepened trough-basin between high mountain slopes characterized by strongly truncated spur-ends and hanging side-valleys; its length is much decreased by the long delta-plain of Kootenay river, which enters the lake from the south after a long detour through Montana from the Rocky mountain trough in which its sources lie; the same river, as the lake outlet, turns westward at mid-length of the lake trough, where a distributary branch of the main glacier scoured out a side trough of catenary cross-profile, with fine hanging side-valleys, but probably 1000 feet less deep than the main trough which holds the lake. Lake Pend Oreille occupies a deep basin of the same kind, that was excavated between two mountain ranges in Montana by the middle one of three terminal branches into which the Kootenay-Pend Oreille glacier was there divided: this lake has been encroached upon by heavy morainic and outwash deposits on the north, which aid in separating it from Lake Kootenay. Huge volumes of gravel were washed southwestward from the terminal moraine at the farther end of Lake Pend Oreille, and now form a terraced intermont plain for 30 or more miles as far as Spokane: several side valleys in the adjoining mountains were barred by the outwashed gravels and now hold lakes, of which the largest is Lake Coeur d'Alene.

Clark fork enters the east side of the broad northern end of Lake Pend Oreille where an arm of the lake would probably have a length of ten or more miles up the river valley but for inwashed gravels; the river flows out from the west side. The two parts of the river, above and below the lake, may be referred to as upper and lower Clark fork. The shortest of the three branches in which the Kootenay-Pend Oreille glacier ended moved westward a score of miles down the valley of lower Clark fork, and supplied the valley beyond its end with a great volume of outwashed gravels, now terraced by the river.

The southeastern terminal branch of the Kootenay-Pend Oreille glacier was remarkable for its long course up the valley of upper Clark fork for 100 miles: its width may have been 10 miles or more near the point of its outbranching, but for much of its length it was less than 5 and sometimes less than 2 miles wide: its greater extension than that of the western branch was probably due to better enclosure between

mountainous highlands and perhaps still more to its being covered for most of its length by the waters of the lake that it ponded, as described below. The work of this long branch glacier in truncating the spurs of the adjoining mountain sides is conspicuous, and gives a peculiarly bold aspect to the valley that it ascended, but with decreasing effect up stream. It was these truncated spurs that caught the attention of the Transcontinental Excursion of the American Geographical Society, when our train ran down the valley from Missoula on the way to Spokane in 1912. We thus passed from the uppermost valley, where the side slopes

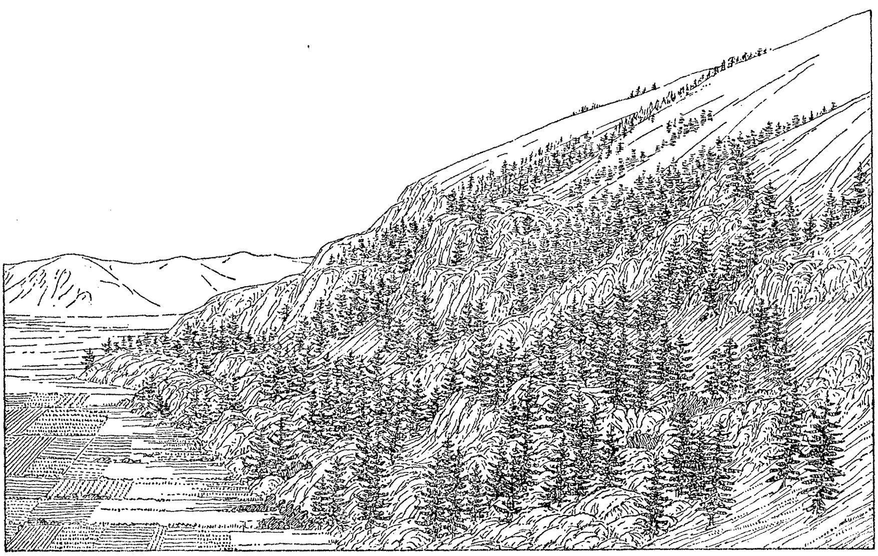

FIG. 2. A TRUNCATED VALLEY-SIDE SPUR, AT PARADISE, MONTANA, LOOKING NORTHWEST.

have normally carved forms, and came unexpectedly on the marks of glacial scouring, faint and low at first, stronger and higher as we proceeded, until the resulting spur-end cliffs gained heights of 500 or 1000 feet, as in figures 2 and 3, and compelled the attention of all observers; I returned there in 1913 for more deliberate study. The contrast between the smooth, maturely rounded forms of normal erosion on the higher, never-glaciated slopes and the ragged, immature cliffs of glacial scouring was as striking as it was persistent. Side valleys are occasionally barred by local moranic embankments, as in fig. 4, and holds swampy hollows behind them: the height of these moraines,

somewhat less than that of the cliff tops, gives the best indication of the local height of the ice margin.

The bare hill sides of the upper valleys of the Clark fork drainage system show many faintly marked shorelines, up to altitudes of 4200 feet; 20 or 24 such lines may be counted, one over the other, in some localities. These have been understood for some years past as recording the occurrence of a temporary lake of fluctuating level, to which the name of Lake Missoula has been given. Pardee pointed out in 1910 that the lake must have resulted from the obstruction of Clark fork by the Canadian glacier at the head of Lake Pend Oreille,[3] where marks of glacial scouring are recognizable in the steepening of the neighboring mountain spur on the south, between Lake Pend Oreille and upper

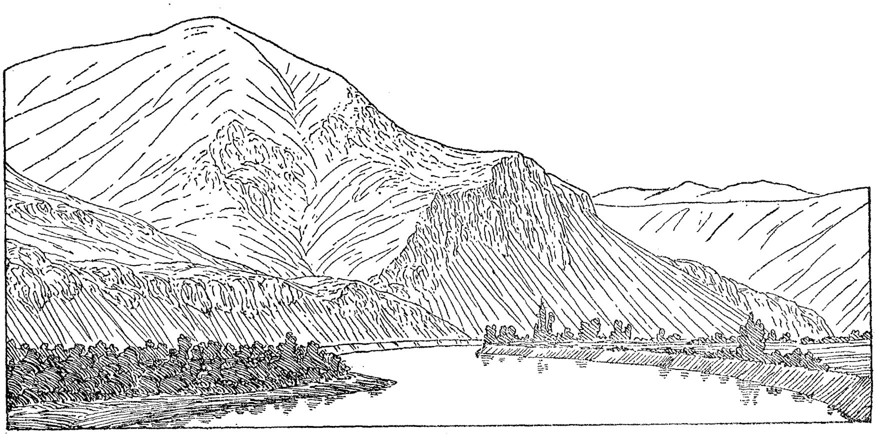

FIG. 3. A STRONGLY TRUNCATED VALLEY-SIDE SPUR, ABOVE PARADISE, MONTANA, LOOKING EAST: CLARK FORK IN FOREGROUND.

Clark-fork valley, up to about the same altitude as that of the highest lake shoreline. The fluctuating level of the lake appears—following the explanation adopted in Sweden for similarly fluctuating glacial lakes—to result from the location of the outlet on the fluctuating surface of the glacier where it impinged on the mountain spur that divided its southern and southeastern branches. It is to be expected that various signs of rushing water should be found on the steepened slope of this spur; unfortunately I had no opportunity of examining that point during my visit of 1913.

Now as the lake shorelines seem to prove that the upper tributary valleys of the Clark fork system were occupied by a lake while the main valley was invaded by the southeastern branch of the Kootenay-Pend

Oreille glacier, and as the lake must have been at its highest level when the branch glacier had its greatest length, it follows that the erosive work of the glacier in truncating the lower ends of the valley-side spurs must have been done under water. The glacier seems to have remained immersed in the lake that it barred because the ice pressed so heavily against the bottom and sides of the valley that no water could enter there to buoy it up. The lake waters at the end of the branch glacier must have been about 1500 feet deep. The same appears to be true of the much broader Canadian glacier in Flathead basin, while it was scouring off the spur-ends on the western slope of the Mission range.[2] The alternative supposition that the glaciers were ordinarily floated up from their valley floors when the lake waters rose, and that they rested on the

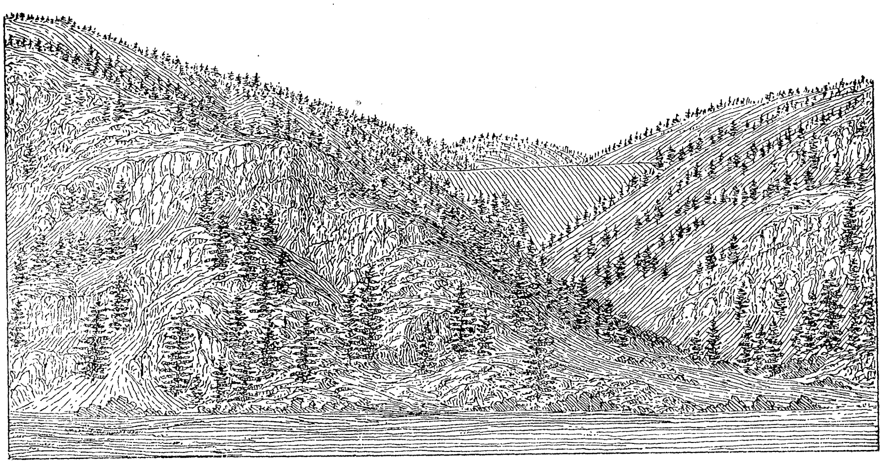

FIG. 4. A SIDE VALLEY BARRED BY A MORAINE, AT PARADISE, MONTANA, LOOKING NORTH

floors and did their erosive work only while the lake was temporarily discharged by leaking through the ice barrier, is, apart from its inherent improbability, not acceptable because the great terminal moraine deposited by the Flathead glacier is of too regular a pattern to have been formed by an agency acting so irregularly.

But the first supposition, on which we are thus thrown back, must also seem inherently improbable; and all the more so when the unfavorable conditions that it imposes on the Clark-fork branch glacier are clearly conceived. This long glacier not only had to creep up a relatively narrow valley that sloped against the direction of glacial advance; it had to creep up the valley against the weight of the lake water in which it was immersed. It is difficult to imagine how the push

from the main glacier could have compelled its narrow branch to advance 100 miles against such discouragements: yet the ice not only did advance 100 miles up Clark-fork valley, but advanced with such insistent pressure that it tore off the resistant rock of the valley-side spurs.

The sublacustrine glacial erosion thus attested takes its place as the last term of a series of unanticipated processes. Seventy years ago, the fiords of Norway, the sea lochs of Scotland, and other similar embayments were interpreted, by those who then accepted Dana's principle of shoreline development, as submerged river valleys. Forty-five years ago, the opinion gained ground that fiord troughs were largely the work of glacial erosion, but the erosion was supposed to have taken place above sea level; the occupation of the troughs by arms of the sea was explained as the result of later submergence. This view was gradually modified by recognizing that a great glacier might erode a trough, if it eroded at all, somewhat below sea level; but the extreme depth of such submarine erosion was placed at about six-sevenths of the thickness of the glacier: at greater depths, the ice would be buoyed up so that it could not erode the trough bottom. Then about twenty years ago Gilbert suggested, as a result of observations that he made in Alaska when a member of the Harriman expedition, that heavy glaciers must press so heavily on their trough beds that water could not enter beneath them; hence such glaciers could erode as well below as above sea level; but it was not supposed that they could be immersed for a score of miles or more. Now the Clark fork branch-glacier seems to have done its visible erosive work on the valley-side spurs—and presumably a considerable amount of invisible work on the valley bottom also—although it must have been wholly immersed in Lake Missoula for two or three score if not for four score miles. It seems impossible for a glacier to perform erosional work under such conditions, yet the erosional work is undeniably visible. Perhaps the conditions of its performance were other than those here indicated, but if so, I have not been able to discover them.

[1] Davis, W. M., these PROCEEDINGS, **1**, 1915, (626–628).
[2] Davis, W. M., *Geogr. Rev.*, **2**, 1916, (267–288).
[3] Pardee, T. G., *Chicago*, *J. Geol. Univ. Chic.*, **18**, 1910, (376–386).